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NONLINEAR EFFECTS AND PARAMETRIC REGENERATION
DURING THE INTERACTION OF WAVES IN WAVEGUIDE SYSTEMS
WITH LONG ELECTRON FLOWS

by S. A. Akhmanov et al.

- USSR -

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NONLINEAR EFFECTS AND PARAMETRIC REGENERATION
DURING THE INTERACTION OF WAVES IN WAVEGUIDE SYSTEMS
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-USSR-

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by S.A. Akhmanov, S.D. Gvozdozer, A.S. Gershtkov,
and V.G. Dmitriyev in the Russian-language publi-
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This is a report on the results of an experimental study of the interaction of waves in waveguide systems with long electron flows. The experiments were carried out in the centimeter and decimeter wavelength ranges with a free-drift electron flow (nonlinear space charge wave interaction) and an electron beam associated with a retarding system (nonlinear interaction of space charge waves with retarding system field). Special attention was devoted to the study of factors determining the effectiveness of parametric regeneration running waves of a small signal by the energy of intensive injection running waves; the ratio of signal and injection frequencies varied over wide limits. It has been established that in systems of this type, as a rule one has to deal with a considerable number of combination frequencies which substantially affect the course of nonlinear and parametric processes.

Introduction

Of increasing interest at present is the study of the propagation and interaction of waves in nonlinear waveguide systems. Studies of phenomena in such systems are described in a number of theoretical papers (see refs 1-4, 10, 15) whose results point to the possibility of obtaining various nonlinear effects. The character of the latter depends on the form of the nonlinearity (active or reactive nonlinearity) and the dispersive properties of the system. Of practical interest are nonlinear phenomena in strou-dispersion waveguide systems where a finite number of waves can interact effectively. Here one can obtain a number of practically interesting applications (parametric amplification, wide-band frequency transformation, modulation, amplitude limiting, etc.).

The experimental study of this complex of questions and the creation of the corresponding radio electronic devices at the present can be carried out with waveguide systems using the nonlinear properties of a solid (waveguide systems with reactive semiconductor nonlinearity (ref 3) or ferrites (ref 4) or waveguide systems employing the nonlinear properties of electron beams (ref 6) or gas discharge plasma (ref 5)).

It should be noted that despite the considerable progress achieved in recent years in the development of nonlinear solid-state reactances, the possibilities of using the latter in wave systems, especially in the uhf (ultra-high-frequency) range, where the indicated phenomena are of the greatest interest, are limited. In present practice it is possible to create only filter-type systems containing nonlinear elements with concentrated constants. On the other hand, using the nonlinear properties of electron flows, it is possible to obtain purely distributed nonlinear waveguide systems with widely varying characteristics.

The subject of the present study are the results of an experimental study of nonlinear wave interaction and especially the phenomena of parametric regeneration in waveguide systems with long electron flows employing the longitudinal interaction of electrons with high-frequency fields. To our knowledge, the experimental study of such systems is described only in ref 6 which deals with the interaction of waves in a free-drift electron flow and does not consider a number of important questions (combination frequency spectrum arising during interaction [see note], the bandwidth of the parametric regeneration mechanism, nonlinear effects, etc.). ([Note:] As far as we know, the first one to point out the fundamental role of higher combination frequencies arising in the process of parametric interaction was A.S. Tagar (ref 1)).

Waveguide systems with long electron flows can be constructed in two ways: with an electron flow drifting freely inside a conducting cylinder (drift tube) and a system in which the electron flow is connected with a retarding line (e.g., a spiral). In both variants, nonlinear effects can be produced upon the introduction into the system of a powerful injection wave as a result of the nonlinearity of the electron flow. If we are interested in parametric regeneration, the possible types of injection and signal waves in the indicated systems can be summarized in a table.

Injection Wave	Signal Wave
1. On electron beam space charge waves (scw)	On electron beam scw
2. On electron beam scw	In retarding system
3. In retarding system	On electron beam scw

It is necessary to note an important difference of system 1 from systems 2, 3 (see table). In system 1 nonlinear effects are determined solely by the nonlinearity of the electron beam. The latter can be regarded as a reactive nonlinearity

inasmuch as the intensity of the electron flow in the process of interaction remains unchanged; the injection and signal voltages are given as boundary conditions at the input of the interaction space. In systems 2, 3 the nonlinearity is of a more complex character (a certain role may also be played by effects associated with the transfer of electron energy to high-frequency fields), while the injection and signal voltages determine not only the boundary conditions, but also the outer forces distributed along the system.

The present study considers the results of an experimental investigation of systems 1 and 2.

#1. Experimental Apparatus: Results of Experiment

2.1. Plan of Experiment

In accordance with the foregoing, the experimental setup envisaged the study of phenomena in the interaction of waves both in a free electron flow and in flow associated with a re-tarding system. It was deemed advisable to carry out the measurements over a wide interval of variation of injection and signal frequencies, power levels, and system parameters. Considerable attention was devoted to the study of the spectrum of combination frequencies arising in the waveguide system under investigation.

The experimental study of the indicated phenomena was carried out on the equipment shown in Fig 1. The object of investigation consisted in electron-waves in the form of running-wave tubes (RWT) with two (Fig 1,a) or three spirals. In the latter case, a free electron drift section was included between the second and third spirals (Fig 1,b). The first spiral in both cases was used for the modulation of the electron flow at the injection frequency f_H ; the signal of frequency f_C was introduced and taken off either through the second spiral (Fig 1,a) or the second and third spirals in the study of phenomena in a free-drift electron flow (Fig 1,b).

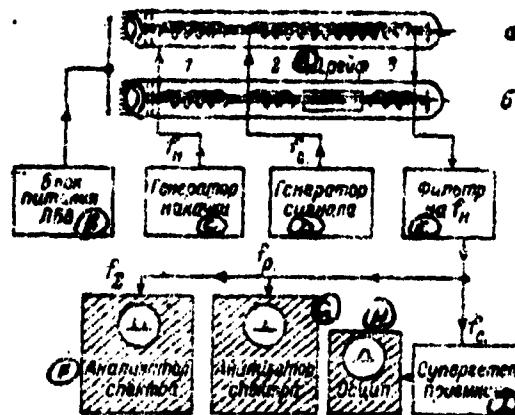


Figure 1. Block diagram of experimental setup.

a -- RWT with two spirals;
b -- RWT with three spirals and electron drift section.
A = Drift; B = RWT power supply;
C = Injection generator; D = Signal generator; E = f_H filter;
F = Spectrum analyzer; G = F; H = Oscillograph; I = Superheterodyne receiver.

Indication of the signal and combination frequencies was carried out with the aid of a superheterodyne receiver and spectral analyzers of the corresponding range; measures were also incorporated for the filtering of injection power at the indicator input. The systems were studied in the centimeter and decimeter wavelength ranges. The inputs and outputs of the experimental systems, depending on the range were either of the waveguide or coaxial type; in the latter case it was possible to study the frequency characteristics of systems.

2.2. Parametric Wave Regeneration in Free-Drift Electron Flow

The study of parametric regeneration in a free-drift electron flow was first carried out with a two-fold ratio of signal and injection frequencies

$$f_{\text{in}} \approx 2f_{\text{c}}.$$

i.e., near the so-called degenerate regime of the basic parametric resonance. It was discovered that in the experimental systems there arose, in particular, waves with a differential frequency $f_{\text{p}} = f_{\text{in}} - f_{\text{c}}$ and the additive frequencies

$$f_{\text{z}_1} = f_{\text{in}} + f_{\text{c}},$$

$$f_{\text{z}_2} = f_{\text{in}} + f_{\text{p}},$$

as well as a wave with a frequency of the injection harmonic $2f_{\text{c}}$. Combination-frequency waves of a higher order were not registered.

As was shown in the experiment, the character of interaction of the space-charge waves in a free-drift electron field depends to a great extent on the accelerating voltage of the drift section V_{ap} (Fig 2). In the absence of flow modulation by injection, the power of signal wave P_{c} varies periodically with drift voltage (curve 1); this periodicity should be ascribed to the interference of the fast and slow space charge waves at the signal frequency (ref 14). Upon the introduction into the flow of the powerful injection wave (an injection power of about 20 mw corresponds to the curves in Fig 2) the picture changes radically: in the region of low accelerating voltages there is a clearly defined region of parametric amplification (to 35 d of the signal wave (curve 2); in the same voltage range one also observes an increase in the power of the differential-frequency wave P_{p} (curve 3). The power of the additive-frequency waves P_{z} (curve 4), as well as of the injection wave harmonic, could be registered only in the region of relatively high accelerating voltages, despite the sufficiently high sensitivity of the spectral analyzers ($\sim 10^{-10}$ watt).

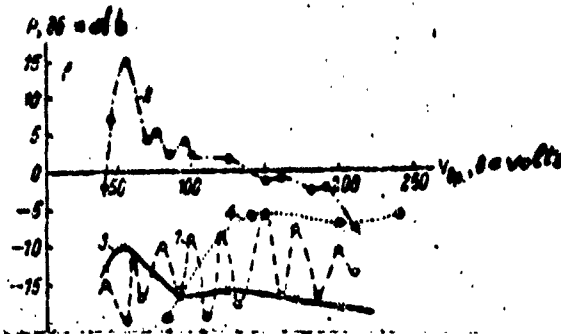


Figure 2. The power of waves of various frequencies (in relative units) as a function of the drift V_{dp} in a free electron flow.

Curve 1 corresponds to the absence of injection; curves 2, 3, 4 characterize the dependence, respectively, of the power of the signal wave P_{s0} , the differential-frequency wave P_{p0} , and the additive-frequency wave P_{a0} on the voltage V_{dp} . Beam current $I_0 = 650$ microamps; $f_{s0} = 2900$ mc/sec; $f_{H0} = 5850$ mc/sec; injection power $P_{H0} \approx 20$ mwt:

$$P_{s0}/P_{s00} \neq P_{p0}/P_{p00} \neq P_{a0}/P_{a00}.$$

Studies of the frequency characteristics of a system with free electron drift showed that parametric regeneration occurs over a very wide range of frequencies (Fig 3). This fact made it possible to pass on to other ratios of the signal and injection frequencies f_H and f_{s0} ; in particular, phenomena were

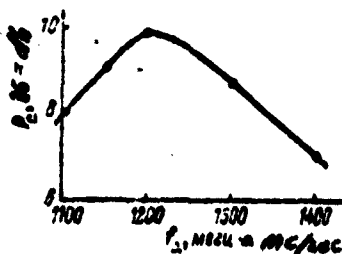


Figure 3. Frequency characteristic of system with electron drift in decimeter range.

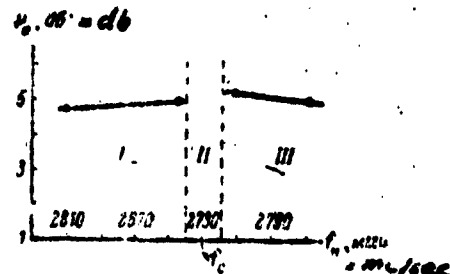


Figure 4. Relative effectiveness of parametric wave regeneration (for signal) with low-frequency (region I) and high-frequency (region III) injection. Region II -- injection filter band.

studied for a signal frequency close to the injection frequency $f_H \approx f_{s0}$. In this case it was possible to investigate the contri-

uous transition from the "high-frequency" injection regime ($f_H > f_c$) to the "low-frequency" injection regime ($f_H < f_c$).

In both cases, no qualitative changes were observed in the character of parametric regeneration. This applies both to the value of parametric amplification (see Fig 4, which shows the dependence of the parametric gain of the signal on injection frequency varying uniformly in the neighborhood of the signal frequency f_c), and to the combination frequency spectrum which

experiences practically no changes with the transition from high- to low-frequency injection.

Let us note that each electrical regime of the experimental systems has a corresponding optimal injection power at the system input. The dependence of signal wave intensity on the input injection power takes the form of a series of increasing maxima.

2.3. Nonlinear Effects in Waveguide Systems Where the Electron Flow is Associated With a Retarding Line

In the study of waveguide systems of the indicated type it was established that the presence of a spiral retarding line considerably alters the picture of wave interaction. The character of the interaction is basically determined by the accelerating voltage of the spiral V_{ca} . This is illustrated by typical

curves of the relative signal wave power and differential and additive frequencies as a function of the spiral voltage (Fig 5). In the absence of modulation on the injection frequency there is a picture typical for R-T's of the interaction of the space charge waves of the signal with frequency f_c in the beam with the signal wave in the spiral (curve 1). Upon introduction into the electron beam (with the aid of supplementary spiral as in Fig 1), of injection waves of frequency $f_H \approx 2f_c$, there appear two characteristic maxima of signal wave regeneration (curve 2) located symmetrically with respect to the region of voltages corresponding to optimal R-T amplification (henceforth we shall call this voltage region the R-T-interaction region). On the contrary, in the region of R-T interaction the introduction of injection leads to a sharp (up to 50-db) suppression of the signal wave.

As in systems with free electron flow, in spiral systems there arises a combination frequency spectrum including the differential and additive frequencies (curves 3 and 4, respectively). It is characteristic that the curves of the regenerated signal and differential frequency have a similar character, while the additive frequency wave can be distinguished only in the R-T-interaction region.

Parametric regeneration in spiral systems, just as in systems with a free electron flow has an extremely wide bandwidth: the band of amplified frequencies in the decimeter wavelength range is about 500 mc/sec with amplification to 20 db. Each electrical regime in the experimental system has a corresponding

injection wave power which is optimal from the standpoint of parametric regeneration; the corresponding dependence has the form of a number of maxima increasing with the power of the injection wave (Fig 6).

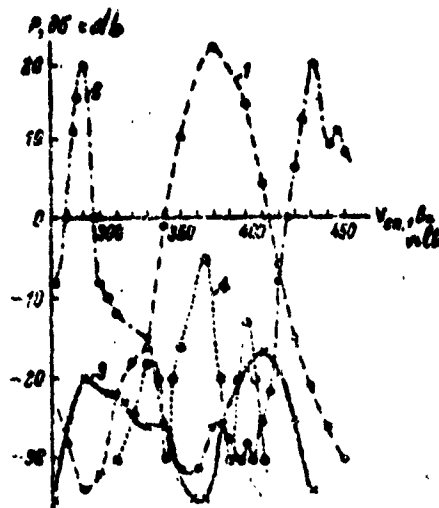


Figure 5. Power of waves of various frequencies (in relative units) as a function of spiral voltage in system where electron flow is associated with retarding spiral line. Curve 1 corresponds to the absence of injection, curves 2, 3, and 4 correspond to the dependence, respectively, of the signal wave differential wave, and additive wave $P_{c.}$, $P_{p.}$, and P_{Σ} on the voltage V_{cn} . The beam current is 650 microamps; $f_{c.} = 2900$ mc/sec; $f_{H.} = 5850$ mc/sec; $P_{H.} = 15 \div 20$ mwt; $P_{c.}/P_{c.0} \neq P_{p.}/P_{p.0} \neq P_{\Sigma}/P_{\Sigma 0}$.

Measurements in the system with the spiral line for $f_{H.} \approx f_{c.}$ were carried out in a conventional RWT whose input received the signal and injection with the aid of a dual triode (the signal and injection generators were operated independently ([Note:] These measurements were carried out by V.N. Yeshtokin). Upon the introduction into the RWT of an injection wave, the phenomena in the system were substantially determined by the spiral voltage. In the center of the RWT-interaction region there was a suppression of the signal by injection, while with spiral voltages exceeding the RWT-interaction potential, the introduction of injection led to some increase in signal intensity. This is illustrated in Fig 7 showing the intensities of the weak signal of frequency $f_{c.} \approx 9440$ mc/sec at the RWT output as a function of the power of the injection wave of frequency $f_{H.} = 9520$ mc/sec. The curve parameter is the spiral voltage: curve 1 was taken in the potential of RWT' interaction, and curve

2 and 3 in the range of voltages higher than the indicated potential. Let us note that in the range of voltages less than

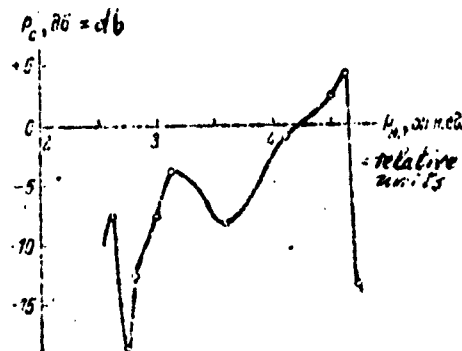


Figure 6. Dependence of the parametric signal wave gain on the injection power P_H in a system where the electron flow is associated with a spiral retarding line for $f_H = 2f_c$.

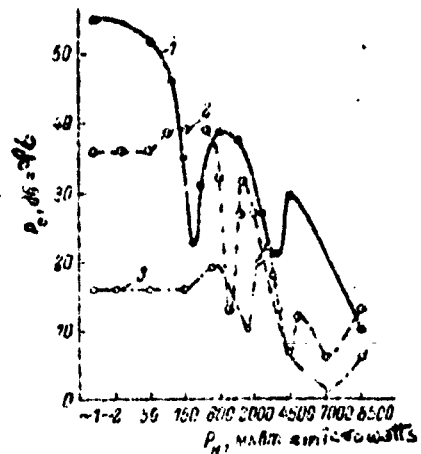


Figure 7. Dependence of the transmission coefficient of flow-spiral line system on injection power P_H for $f_H \approx f_c$ and various spiral voltages. Curve 1 taken with RWT-interaction voltage; curves 2 and 3 taken at higher voltages.

RWT-interaction potential, one observed only signal suppression by injection. The strong dependence of weak signal intensity on injection power illustrated in Fig 7 is the reason for the experimentally-observed cross-modulation phenomenon. This phenomenon, consisting in the transfer of modulation from the injection wave to the signal wave, can be of some interest from the standpoint of both modulation transference and the possibility of creating a modulation amplifier.

#2. Discussion

At the present time, as far as we know, there is no sufficiently complete theory of parametric wave interaction in nonlinear waveguide systems ([Note:] Refs 12 and 13 are of some interest in this connection). In the selection of experimental system parameters and in order to obtain quantitative concepts of the character of the parametric regeneration process, analysis based on the consideration of the dispersive characteristics of systems and the general principles of the theory of parametric interaction in waveguide systems is convenient. Let us turn first of all to the consideration of experimental data on wave interaction in a free electron flow.

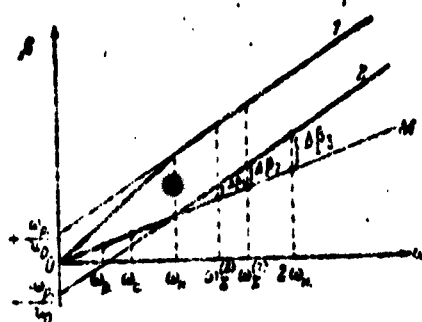


Figure 8. Dispersion characteristics of slow (1) and fast (2) space charge waves in free electron flow. The synchronism line OM corresponds to the case of an absence of dispersion.

In the general case in a nonlinear waveguide system such as the electron flow, upon the interaction of the signal wave of frequency f_0 with the injection wave of frequency f_H , there is formed a spectrum of combination frequencies

$$f_{mn} = mf_H \pm nf_0. \quad (1)$$

The intensity of the wave generated at some combination frequency f_{mn} is substantially determined by the shift with respect to the propagation constants β between the indicated wave and the signal and injection waves

$$\Delta\beta_{mn} = \beta_{mn} - (f_{mn}/f_{0,H}) \cdot \beta_{0,H}. \quad (2)$$

In a dispersionless system all the β_{mn} are equal to zero; increasing waves do not arise. The latter possible only in a dispersive system where the energy exchange is considerable for a finite number of waves. Under certain conditions, such a system is an electron beam whose dispersion characteristics are given by the equation

$$\beta(f) = (2\pi f/u_0)(1 \pm R\omega_p/2\pi f), \quad (3)$$

where the signs " \pm " correspond to the slow and fast space charge waves at the frequency f ; $R\omega_p$ is the reduced plasma frequency for a finite cross-section beam; u_0 is the electron velocity. Schematically, the dispersive characteristics (3) are shown in Fig 8, where we likewise see the shifts (2) for the additive frequencies and injection harmonic.

The indicated shifts [see note] increase with rising frequency; as a result of this, only a finite number of waves practically take part in the electron flow in the process of parametric interaction. ([Note:] Results of a precise calculation lead to a system of equations for the amplitudes of waves V_1 and phases Φ_1

$$dV_1/dz = a_1 V_1 V_k \sin \Phi_k + a_1 V_1 V_k \sin \Phi_j + \dots,$$

$$d\Phi_1/dz = \Delta_1 + a_k (V_1 V_j / V_k) \cos \Phi_j + \dots,$$

where a_i are constant coefficients; $\Delta_1 = \Delta\beta_{H_1} - \Delta\beta_k - \Delta\beta_1$; $\Delta\beta_k$, $\Delta\beta_1$ are the shifts of the injection and the k-th and 1-th combination frequencies, respectively, relative to the synchroni line. For this reason, strictly speaking, the intensity of regeneration of a certain combination wave is determined by the shift Δ_1 , and not $\Delta\beta_{mn}$ (2). However, the character of variation of the shift Δ_1 in the system parameter function is the same as that of $\Delta\beta_{mn}$, so that the more convenient shifts $\Delta\beta_{mn}$ were used for qualitative evaluations).

From expression (3) and Fig 8 we see that the dispersion of space charge waves in the beam is substantially determined by the accelerating voltage of the electron drift section; in particular, the dispersion increases with the reduction of the indicated voltage. There is a corresponding decrease in the number of combination waves effectively participating in interaction with signal and injection waves, while the effectiveness of the parametric regeneration of the signal wave increases. With very small drift potentials, the shift in signal and injection wave phase velocities begins to play a significant role; here we can likewise have the effect of potential sag in the beam (see ref 7) which leads to signal cutoff.

The indicated factors lead to some optimal voltage of the drift section from the standpoint of parametric regeneration

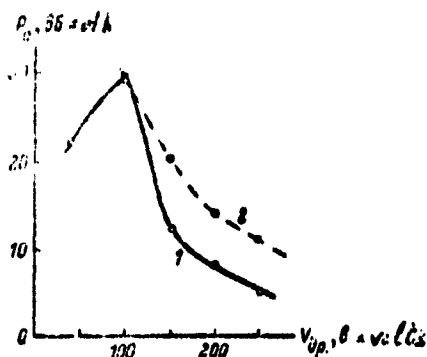


Figure 9. Dependence of parametric signal wave gain on drift voltage in free electron flow. 1 -- experimental curve; 2 -- theoretical curve calculated taking into account only the signal waves and differential frequency.

The fall in signal wave intensity with increasing drift voltage can be explained both by the reduction of beam dispersion and the related increasing effect of waves of higher combination frequencies and the reduction of effective beam length. The effect of the latter can be evaluated from the signal amplification formula (ref 9) which takes into account only the signal and differential frequency waves

$$G = 41mN_q \quad (4)$$

(m is the modulation coefficient; N_q is the number of plasma wavelengths over the length of the drift section). In Fig 9, curve 2 is calculated, in accordance with (4), with $m = 0.7$. In actuality, the drop in signal intensity with increasing voltage can occur much faster (curve 1), and this can be explained by the interaction of signal waves and injection waves with waves at the higher (additive, et al.) combination frequencies.

As shown in calculations, to explain the periodic dependence of signal power on the injection wave power (Fig 6), as well as phenomena with low-frequency injection, it is necessary to take in a considerable number of combination frequencies (see footnote above). The indicated periodicity can be explained by the transformation of the signal wave and differential-frequency wave energy into the energy of additive-frequency wave energy, and vice-versa, for example (ref 8).

The low-frequency injection system in the investigated weak-dispersion systems does not differ in principle from the regime of high-frequency injection; the initial equations (see footnote above) in both cases differ only in the conditions at the system input. Here the frequency spectra of waves taking part in the interaction are wholly equivalent. As shown by qualitative calculations for the electron flow model in the form of an equivalent transmission line, an exponential rise in the wave amplitudes in the case of high-frequency injection ($f_H \approx 2f_c$) is possible upon the inclusion of the differential frequency wave only, while in the case of low-frequency injection it is necessary to take into account waves with the additive and the two differential frequencies. Apparently, in the latter case the low-frequency injection of frequency $f_H < f_c$ plays the role of high-frequency injection with respect to the differential frequency $f_p = f_H - f_c$; to have an increase in the wave amplitude at the frequency f_p it is necessary for the wave with the second differential frequency $f_H - f_p$ to be present. Here the signal frequency turns out to be an equivalent "additive" frequency.

It should be pointed out that in the case of low-frequency injection a definite role can be played by parametric regenerative processes at the higher parametric resonance frequencies ($f_H \approx f_p \approx 0.5f_c$). However, the threshold flow modulation coefficient at the injection frequency rises considerably.

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The character of the nonlinearity of the waveguide system is considerably complicated if the electron flow permeates the spiral retarding system. A considerable role can be played by the energy exchange between the electron flow and the high-frequency fields of the spiral. Thus, the powerful injection wave can bring the RWT into a radically nonlinear regime (with an accelerating voltage which is optimal for amplification). As a result of this, there is a disruption of the synchronism between the slow waves in the beam and the spiral waves; the spiral potential optimal for amplification rises, and the intensity of combination frequency generation increases substantially. The above facts lead to a sharp suppression of the signal upon the introduction of a powerful injection wave (Fig 6).

The wave synchronism in the flow and spiral is reestablished upon some increase of the accelerating voltage; this fact may be one of the causes of the appearance of a right-hand maximum of parametric regeneration (Fig 5).

On the other hand, a definite role may be played by the interaction of space charge signal and injection waves in the beam itself and the interaction of the powerful injection wave in the beam with the signal wave in the spiral. The latter mechanism apparently predominates in the parametric regeneration region of the wave in the spiral by the fast wave of the injected space charge.

The relatively weak dispersion of the beam-spiral system is the cause of the band breadth of the system. The band of amplified frequencies of the signal is about 40% with a parametric amplification of up to 20 db. The interaction of the injection and signal waves with higher-frequency combination waves leads to a periodic dependence of the intensity of the regenerated signal wave on the power of the injection wave.

It is necessary to note that the described experimental systems were made up of RWT amplifiers whose operating point was on the downward portion of the spiral dispersion characteristic, while the relatively high acceleration voltage in the spiral optimal for amplification assured low beam dispersion. The increasing of the dispersion of such a system is advisable in view of the possibility of cutting off the undesirable combination frequencies.

Conclusion

The results of the above study indicate the possibility of obtaining varied nonlinear effects in waveguide systems with long electron flows (parametric amplification with low- and high-frequency injection, suppression, cross-modulation, limiting, etc). An especially significant effect on the character of the indicated phenomena is exerted by the dispersive properties of the system. It should be emphasized that in a system of the type described, wave interaction is as a rule associated with the generation of a wide combination-frequency spectrum.

Many of the effects considered can be explained on the basis of an analysis of the dispersive characteristics of system and general assumptions of the theory of wave interaction in nonlinear wave systems encompassing a large number of combination frequencies.

A number of observed phenomena can, in our view, be of some practical interest and require further experimental and theoretical investigation.

The authors take this opportunity to express their sincere appreciation to D.K. Akulin and I.A. Dubov for their assistance in carrying out the present study and for valuable discussion.

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